

LFC - A MATURING CONCEPT*

John Morris
Douglas Aircraft Company
McDonnell-Douglas Corporation
Long Beach, California

* Douglas Paper 7878.

INTRODUCTION

The existence of both turbulent and laminar flows has been known for a long time, but it was not until the middle of the last century that the first systematic tests with fluids were conducted to establish the physical relationships and governing laws. The importance of turbulent and laminar airflows in aeronautics was recognized as early as the 1930s, but actual laminar flow control (LFC) investigations were not undertaken seriously until the 1940s.

This overview briefly touches on some of the historical developments of LFC leading up to current activities. It then examines the technical problems being addressed and potential long-term LFC applications. Past and current Douglas activities are examined and the required future testing involving hybrid laminar flow control (HLFC) is discussed (Figure 1).

1. HISTORICAL DEVELOPMENT OF LFC
2. TECHNICAL PROBLEMS ADDRESSED
3. POTENTIAL LONG-TERM APPLICATION
4. DOUGLAS PAST AND CURRENT ACTIVITIES
5. REQUIRED FUTURE TESTING: HLFC

FIGURE 1. LFC OVERVIEW

There are three principal laminarization technologies for aircraft:

1. Natural laminar flow (NLF) for moderately swept wings (generally less than 21 degrees) relying on a favorable pressure gradient. This concept is most suitable for general aviation aircraft.
2. Suction laminar flow control (LFC), which can laminarize highly swept wings with significant cross-flow and attachment line instabilities, and with adverse pressure gradients. The total potential for LFC includes wings, tails, nacelles, and "clean" regions of fuselages.
3. Hybrid LFC (HLFC), which is based on suction LFC from leading edge to front spar and natural laminar flow aft of the spar. This is the simplest and most economical suction LFC application (Figure 2).

NATURAL LAMINAR FLOW (NLF)

- MODERATELY SWEEPED WINGS, \angle - 21 DEGREES
- FAVORABLE PRESSURE GRADIENT
- SUITABLE FOR GENERAL AVIATION

SUCTION LAMINAR FLOW CONTROL (LFC)

- CAN LAMINARIZE HIGHLY SWEEPED WINGS WITH CROSS-FLOW AND ATTACHMENT LINE INSTABILITIES AND ADVERSE PRESSURE GRADIENTS
- POTENTIAL FOR MAXIMUM LAMINARIZATION OF WINGS, TAILS, NACELLES, AND "CLEAN" REGIONS OF BODIES

HYBRID LFC (HLFC)

- SUCTION LFC FROM LEADING EDGE TO FRONT SPAR
- NATURAL LAMINAR FLOW AFT OF SUCTION REGION
- SIMPLEST/MOST ECONOMICAL SUCTION LFC APPLICATION

FIGURE 2. PRINCIPAL LAMINARIZATION TECHNOLOGIES FOR AIRCRAFT

HISTORICAL DEVELOPMENT OF LFC

The initial suction LFC investigations (Figure 3) were conducted in the 1940s by the British, Germans, and Swiss in Europe and by NACA in the United States. During the next decade, Northrop and the U.S. Air Force developed and tested a slotted LFC glove concept on an F-94 aircraft. At Mississippi State University, experiments were conducted using a glider with a fabric wing and pricked perforations. Finally, at the RAE in Great Britain, a de Havilland Vampire (Figure 4) was equipped with a coarse perforated glove and flown extensively. This was followed in the 1960s by the most ambitious program undertaken until then — the X-21 (Figure 5). A Northrop/USAF project, the X-21 was a derivative of the B-66 with a new wing featuring suction slots on both upper and lower surfaces. One pod under each wing housed the compressors for the suction systems.

The experience from these different development efforts was largely encouraging, but much work still remained until a truly practical solution would emerge. Laminar flow was achieved over major portions of the X-21 wing, but difficulties were experienced, in particular with the more demanding inboard sections close to the fuselage.

One objective of this LFC testing was to improve the range capability of military aircraft at a time when jet engines still displayed poor fuel efficiency. However, at that time the bypass engines began to emerge and the interest in LFC faded,

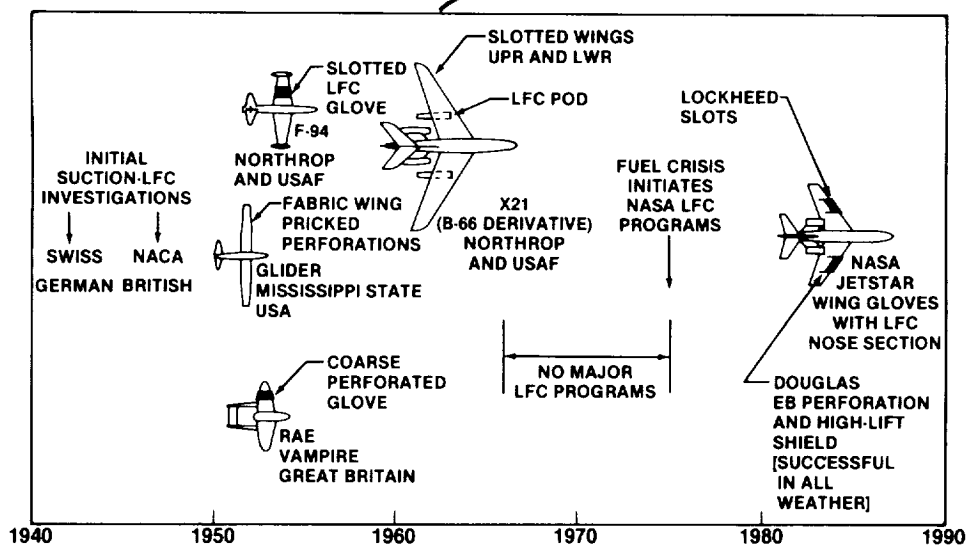


FIGURE 3. SUCTION-LFC FLIGHT TEST PROGRAMS

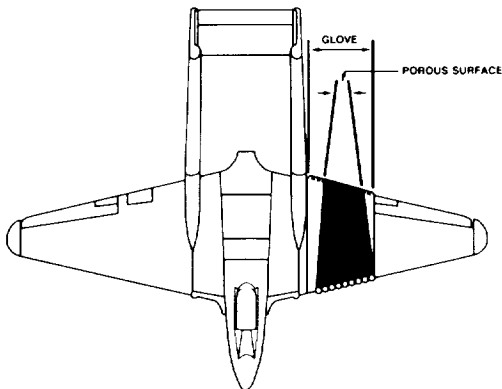


FIGURE 4. DE HAVILLAND VAMPIRE EQUIPPED WITH COARSE PERFORATED GLOVE

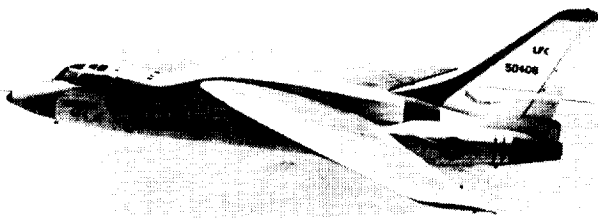


FIGURE 5. X-21 LFC TEST PLANE

remaining low for approximately a decade until the fuel crisis struck the industry and NASA initiated LFC programs in the mid-1970s.

The current NASA Jetstar program has been highly successful, yielding invaluable experience with two different approaches: the Douglas electron-beam-perforated approach on one wing and the Lockheed slot system on the other. The Douglas system will be discussed later in this paper.

TECHNICAL PROBLEMS AND SOLUTIONS FOR LFC

A number of practical technical problems have been identified, and the required solutions have been developed by industry and tested in flight by NASA (Figure 6). The solution to the leading edge problems of contamination and/or icing is clearly the retractable shield in combination with liquid efflux.

Wing sweep created the problems of attach line instability and cross-flow instability. The successful solution here is distributed suction with perforations that are not sensitive to the flow direction.

Other problems are related to surface characteristics such as roughness, steps, gaps, and variances. The solutions here involve close-tolerance external jig control or accurate mold surfaces, and the avoidance of surface joints or slots that can cause discontinuities.

Finally, there are potential problems with the suction involving boundary layer disturbance and clogging. The solutions have been provided by the electron beam (EB) technology,

| PROBLEMS | SOLUTIONS |
|---|---|
| LE: CONTAMINATION ICING | RETRACTABLE SHIELD LIQUID EFFLUX |
| SWEEP: ATTACH LINE INSTABILITY CROSS-FLOW | DISTRIBUTED SUCTION WITH PERFORATIONS |
| SURFACE: ROUGHNESS STEPS GAPS WAVINESS | EXTERNAL JIG CONTROL ACCURATE MOLD SURFACES CONTINUOUS SURFACES |
| SUCTION: BOUNDARY LAYER DISTURBANCE CLOGGING | FINE PERFORATIONS TAPERED PERFORATIONS EB TECHNOLOGY |

FIGURE 6. TECHNICAL PROBLEMS AND SOLUTIONS FOR LFC

which generates extremely fine perforations of the desired high density and tapers these perforations to prevent clogging.

POTENTIAL LONG-TERM APPLICATION OF LFC

The potential long-term applications of LFC are substantial (Figure 7). However, additional testing must be done before LFC can be applied with confidence on production airplanes. The initial application will center around the hybrid laminar flow control (HLFC) solution, which promises a drag reduction of about 10 percent. Further gains are possible by using suction in other regions of the wing, the horizontal and vertical tails, the nacelles, and certain "clean" regions of the fuselage. Total drag improvements could then eventually reach as much as 25 percent, with the actual levels depending on the extent of complexity justified by future fuel costs for optimum economics.

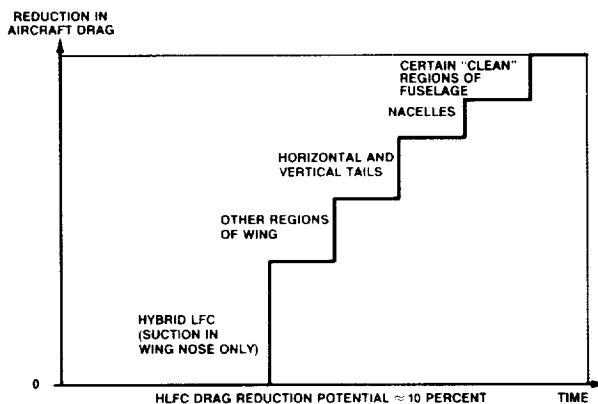


FIGURE 7. POTENTIAL LONG-TERM APPLICATION OF LFC

PAST AND CURRENT DOUGLAS ACTIVITIES

Three major developments that resulted from past Douglas LFC efforts are listed in Figure 8 and will be discussed in detail later. These developments have been instrumental in helping to correct some of the shortcomings encountered in the early LFC tests, both in Europe and the U.S. In particular, as shown in Figure 9, the previous LFC suction surfaces left much to be desired. Slotted surfaces involved difficult and costly machining, and surface deformation frequently occurred as the slots released locked-in stresses. Furthermore, spanwise flow along the attachment line, including fuselage boundary layer contamination, could not be controlled using spanwise suction slots. A porous surface offers a better solution since it is not sensitive to the flow direction, which changes rapidly in the leading edge region.

ELECTRON-BEAM-PERFORATED SUCTION SURFACE

SIMPLIFIED LFC SUCTION PANEL

RETRACTABLE HIGH-LIFT SHIELD

FIGURE 8. LFC TECHNOLOGY DEVELOPMENTS AT DOUGLAS

The earlier porous surface obtained through the sintering process was easily clogged. It was poor structurally and multiple sintered inserts resulted in inadequate joint smoothness. Other perforation techniques available at the time resulted in holes that were too large, and mechanical drilling proved to be prohibitively expensive.

SLOTTED SURFACES

- MACHINING DIFFICULT AND COSTLY
- SURFACE DEFORMATIONS AFTER SLOTTING
- ATTACHMENT LINE INSTABILITY
- FUSELAGE BOUNDARY LAYER CONTAMINATION

} SPANWISE FLOW

POROUS SURFACES

- SINTERED
 - CLOGGING
 - POOR STRUCTURALLY
 - JOINT SMOOTHNESS
- PERFORATED
 - PRACTICAL HOLES TOO LARGE
 - MECHANICAL DRILLING TOO EXPENSIVE

FIGURE 9. PREVIOUS PROBLEMS WITH LFC SUCTION SURFACES

Douglas selected EB-perforated titanium for LFC suction surfaces, as shown in Figure 10. This process economically produces sufficiently fine tapered perforations with satisfactory accuracy and consistency. The outstanding characteristics of this approach are listed in Figure 11. Foremost are high wing strength and stiffness, both in bending and torsion with uniform porosity unaffected under load. Furthermore, the panel is corrosion- and damage-resistant and can be readily repaired. Any local reduction in porosity following repair will not cause a loss of LFC. Finally, the external airflow direction is not critical. A number of large LFC panel structural test specimens with EB-perforated surfaces have been built and successfully tested (Figure 12). The panel strength and strain characteristics exceeded those required for wing panels of either aluminum or carbon composite construction.

Initially, Douglas visualized the entire upper wing surface under LFC suction with an arrangement as shown in Figure 13. The integral suction flow channels in the panel that lead to the wing flow channels and spanwise ducts are clearly visible. Also shown is the retracted leading edge high-lift

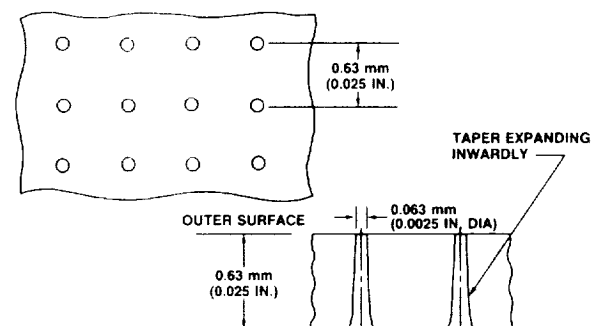


FIGURE 10. SUCTION SURFACE ELECTRON-BEAM-PERFORATED TITANIUM

HIGH STRENGTH - CONTRIBUTES TO WING STRENGTH AND STIFFNESS IN BENDING AND TORSION
POROSITY UNIFORM - UNAFFECTED BY STRESS/STRAIN
DOES NOT CLOG - SELF-CLEARING BECAUSE OF TAPERED HOLES
- SIMPLE STEAM CLEANING EFFECTIVE
CORROSION-RESISTANT
DAMAGE-RESISTANT - REPAIR PRACTICAL
EXTERNAL AIRFLOW DIRECTION NOT CRITICAL

FIGURE 11. ELECTRON-BEAM-PERFORATED TITANIUM CHARACTERISTICS

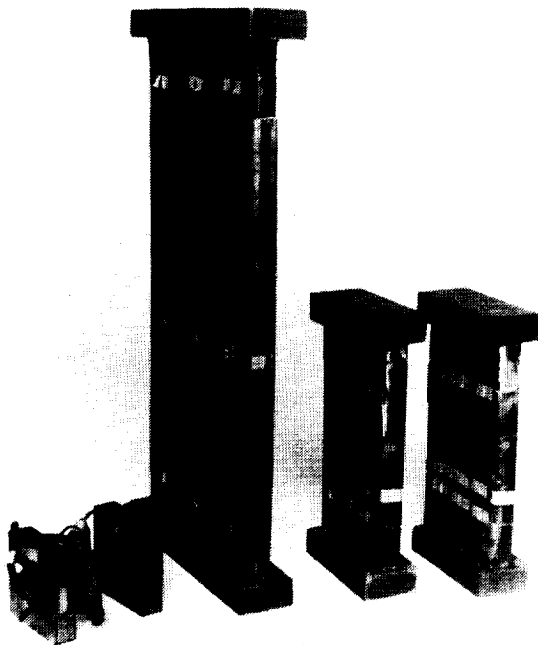


FIGURE 12. LFC PANEL STRUCTURAL TEST SPECIMENS

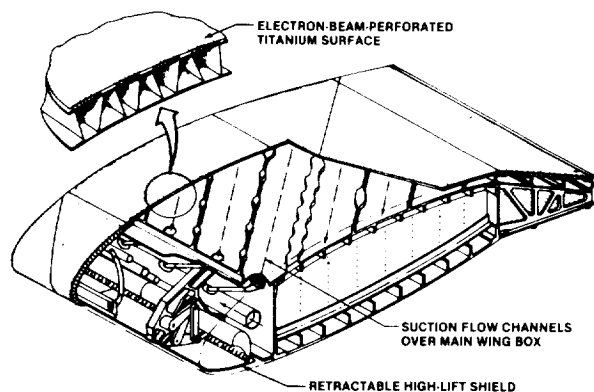


FIGURE 13. DOUGLAS/NASA POROUS-UPPER-SURFACE LFC CONCEPT

device, which acts as a shield to prevent surface contamination at low altitudes, particularly during takeoff, approach, and landing.

While analyzing this concept, it became clear that there are many advantages in laminarizing only the upper wing surface (Figure 14). LFC is used most effectively on that surface, which causes two-thirds of the total wing skin friction, particularly with an efficient wing that cruises at a high-lift coefficient. This is possible with the high-lift shield that allows the use of a smaller wing, thereby eliminating any sizing penalty relative to an advanced turbulent wing, which obviously would have a leading edge device. Other benefits are easy access to wing systems; a simpler, less expensive suction system; and lower maintenance cost.

TWO-THIRDS OF TOTAL SKIN FRICTION ON UPPER SURFACE
(LFC USED MORE EFFECTIVELY)
ALLOWS USE OF RETRACTABLE HIGH-LIFT SHIELD
(SMALLER WING WITH HIGHER C_{LMAX} + CONTAMINATION AVOIDANCE)
NO SIZING PENALTY RELATIVE TO ADVANCED TURBULENT WING
LAMINAR SURFACE NOT EXPOSED TO FOD
ALLOWS NORMAL ACCESS TO WING SYSTEMS
SIMPLER SYSTEM WITH LOWER COST
LESS SUCTION POWER REQUIRED
LOWER MAINTENANCE COST

FIGURE 14. ADVANTAGES OF LAMINARIZING UPPER WING SURFACE ONLY

The large LFC high-speed wind tunnel panels shown in Figure 15 were manufactured by Douglas. They have been installed on the swept-wing model now being tested by NASA in the 8-foot tunnel at Langley.

Douglas participated in the extensive NASA Jetstar flight test program (Figure 16). The objective was to demonstrate the effectiveness of LFC leading edge systems under representative flight conditions. The starboard wing was equipped with the Douglas EB-perforated wing panel (Figure 17) and related equipment and systems, while the port wing carried corresponding installations using the Lockheed slot system. The Douglas concept is illustrated in Figure 18, which shows the suction panel and the small retractable shield with its de-icing system and supplementary fluid spray nozzles. In addition to the LFC leading edge system performance, the contamination avoidance system was tested in simulated airline service operations. These tests were conducted from three different bases (Figure 19) into a variety of airports to obtain a representative cross section of operational conditions with regard to climate, environment, and seasonal fluctuation.

The small leading edge shield was found to provide very effective protection against the kind of insect contamination that can be encountered at lower altitudes. The results from one particular flight without use of the liquid system, are shown in Figure 20. The contrast to the unprotected left wing is striking.

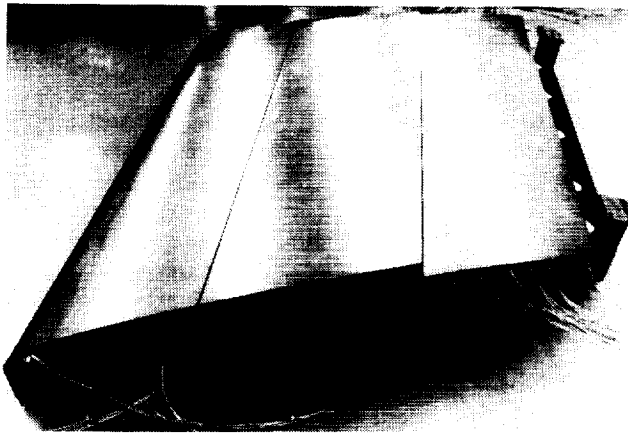


FIGURE 15. LFC HIGH-SPEED WIND TUNNEL PANELS

OBJECTIVE

- DEMONSTRATE BY FLIGHT RESEARCH THE EFFECTIVENESS OF LFC LEADING EDGE SYSTEMS UNDER REPRESENTATIVE FLIGHT CONDITIONS

FLIGHT TEST PROGRAM

- LFC LEADING EDGE SYSTEM PERFORMANCE
- CONTAMINATION AVOIDANCE SYSTEMS PERFORMANCE
- SIMULATED AIRLINE SERVICE OPERATIONS

FIGURE 16. LFC JETSTAR FLIGHT TEST PROGRAM

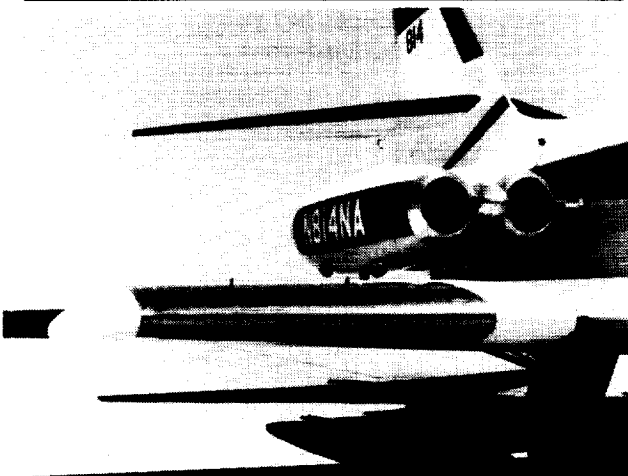


FIGURE 17. LAMINAR FLOW CONTROL

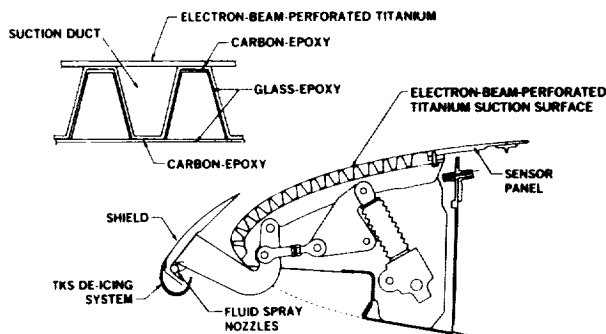


FIGURE 18. DOUGLAS TEST ARTICLE

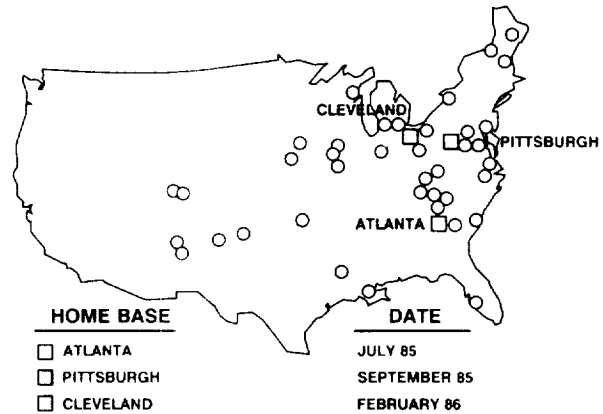


FIGURE 19. SIMULATED SERVICE FLIGHT TESTS

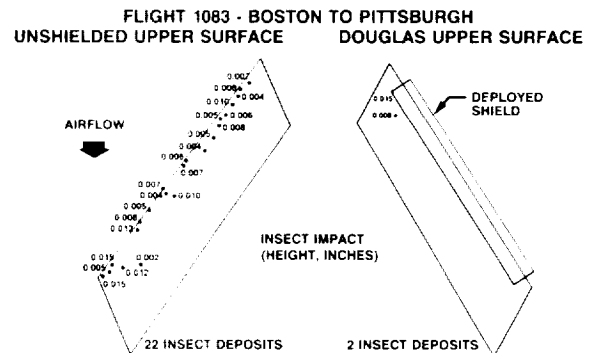


FIGURE 20. INSECT CONTAMINATION ON JETSTAR DURING DESCENT

Other aspects of airline service simulation involved overnight accumulation of ice and snow on the wings (Figure 21) with subsequent removal through normal glycol spraying before flight (Figure 22), which proved entirely adequate for subsequent LFC operation.

In summary, the performance of the Douglas LFC system during 3 years of flight testing has been excellent (Figure 23). LFC was achieved on the initial test flight. LFC was lost only during flights through ice crystals, but was immediately restored when clear air was reached. Overall, LFC was reliably obtained throughout simulated airline service flying that reflected a wide variety of winter and summer conditions, including ice, snow, heavy rain, and airborne insect infestation. No surface maintenance has been needed, and there has been no deterioration of the LFC panel or its performance during the 3 years of flight testing.

REQUIRED FUTURE TESTING: HLFC

A simpler approach to achieving LFC on swept wings is currently under investigation. In this approach, suction is used only in the leading edge region to counteract attachment line and cross-flow instabilities, and a favorable pressure gradient



FIGURE 21. OVERNIGHT ACCUMULATION OF ICE AND SNOW

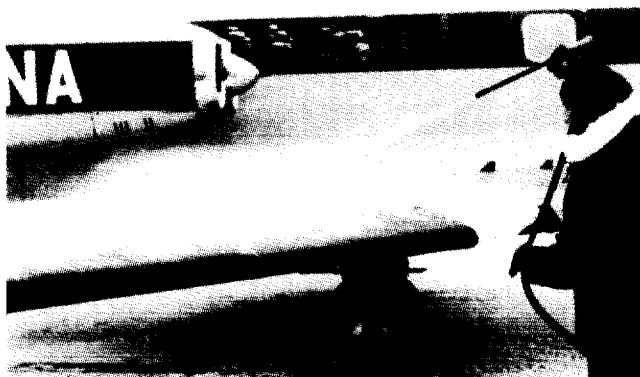


FIGURE 22. GLYCOL SPRAYING BEFORE FLIGHT

LFC ACHIEVED ON INITIAL TEST FLIGHT

LFC RECOVERED IMMEDIATELY FOLLOWING FLIGHT THROUGH ICE CRYSTALS

LFC OBTAINED RELIABLY THROUGHOUT SIMULATED AIRLINE SERVICE FLYING - 59 FLIGHTS/45 AIRPORTS

- SUMMER:
 - AIRBORNE INSECT INFESTATION
 - HEAVY RAIN STORMS
- WINTER:
 - OVERNIGHT EXPOSURE TO ICE AND SNOW
 - IN-FLIGHT ICING CONDITIONS

NO DETERIORATION OF LFC POROUS SURFACE OR PERFORMANCE IN 3 YEARS OF FLIGHT TESTING

FIGURE 23. PERFORMANCE OF DOUGLAS LFC LEADING EDGE DURING JETSTAR FLIGHT TESTS

is used further aft to maintain laminar flow over the main wing box region (Figure 24).

This concept, known as hybrid laminar flow control (HLFC), offers many advantages (Figure 25). These include reduced suction power requirements, simplification of the suction system, uncompromised wing structural efficiency and fuel volume, and reduced initial cost and maintenance requirements. This concept needs to be tested in flight.

OBJECTIVE - ECONOMICAL LFC WITH EFFICIENT STRUCTURE

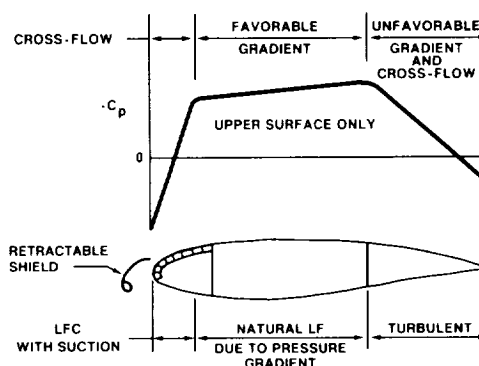


FIGURE 24. HYBRID LAMINAR FLOW CONTROL (HLFC)

SIMPLEST PRACTICAL LFC SYSTEM

LESS SUCTION POWER REQUIRED

WING BOX STRUCTURE AND FUEL TANK UNAFFECTED

LOWER INITIAL COST

LOW INVESTMENT RISK

- SAME AIRFOIL SECTION AS TURBULENT DESIGN

REDUCED MAINTENANCE COST

FIGURE 25. ADVANTAGES OF HLFC

The objectives of such full-scale testing are numerous. Apart from demonstrating the basic HLFC concept at an appropriate Mach number and Reynolds number, environmental effects and off-design flight performance can be investigated. The results of this program, if successful, can reduce design risks in making future industry applications.

DOUGLAS LFC PROGRAM SUMMARY

The electron-beam-perforated suction surface and its simplified suction ducting has been shown to provide reliable leading edge LFC in flight, and the high-lift shield effectively protects the LFC surface from contamination.

The development of needed technology for a practical and reliable LFC system is thus already well advanced. However, HLFC is so far an unproven concept, and full-scale flight testing is clearly needed to further advance the state of the art (Figure 26).

EB-PERFORATED SUCTION SURFACE IS PROVIDING RELIABLE LFC ON LEADING EDGE IN FLIGHT

HIGH-LIFT SHIELD IS PROTECTING LFC SURFACE EFFECTIVELY

DEVELOPMENT OF TECHNOLOGY NEEDED FOR A PRACTICAL AND RELIABLE LFC SYSTEM IS ALREADY WELL ADVANCED

HLFC IS AN UNPROVEN CONCEPT THAT NEEDS TO BE TESTED

FIGURE 26. DOUGLAS LFC PROGRAM SUMMARY

